Fueling the Future:
The Road to the Hydrogen Economy

Statement of

Dr. David L. Bodde
Professor and Senior Fellow

International Center for Automotive Research
Arthur M. Spiro Center for Entrepreneurial Leadership

Clemson University

Presented to the

Committee on Science:
Subcommittee on Research and Subcommittee on Energy
U.S. House of Representatives

20 July, 2005

Thank you, ladies and gentlemen, for this opportunity to discuss the *Road to the Hydrogen Economy*, a road I believe we must travel if we are to ensure a world well supplied with clean, affordable energy derived from secure sources. I will speak to this from the perspective of motor vehicle transportation and address the questions posed by the Committee within the framework of three basic ideas.

First, research policy should view the hydrogen transition as a marketplace competition. For the next several decades, three rival infrastructures will compete for a share of the world auto market: (a) the current internal combustion engine and associated fuels infrastructure; (b) the hybrid electric vehicles, now emerging on the market; and (c) the hydrogen fueled vehicles, now in early demonstration. We can judge policy alternatives and applied research investments by their ability to accelerate the shift in market share among these competing infrastructures.

Second, and in parallel with the marketplace transition, fundamental research should focus on sustaining the hydrogen economy into the far future. Key issues include: (a) storing hydrogen on-board vehicles at near-atmospheric pressure; (b) sequestering the carbon-dioxide effluent from manufacturing hydrogen from coal; (c) sharply reducing the cost of hydrogen produced from non-coal resources, especially nuclear, photobiological, photoelectrochemical, and thin-film solar processes; (d) improving the performance and cost of fuel cells; and (e) storing electricity on-board vehicles in batteries that provide both high energy performance and high power performance at reasonable cost.

And third, the results of this research must be brought swiftly and effectively to the marketplace. This requires economic policies that encourage technology-based innovation, both by independent entrepreneurs and those operating from the platform of established companies. Clemson University, through its International Center for Automotive Research and its Arthur M. Spiro Center for Entrepreneurial Leadership, intends to become a major contributor to this goal.

In what follows, I will set out my reasoning and the evidence that supports these three basic ideas.

THE HYDROGEN TRANSITION: A MARKETPLACE COMPETITION

Much thinking about the hydrogen economy concerns “what” issues, visionary descriptions of a national fuels infrastructure that would deliver a substantial fraction of goods and services with hydrogen as the energy carrier. And yet, past visions of energy futures, however desirable they might have seemed at the time, have not delivered sustained action, either from a public or private perspective. The national experience with nuclear power, synthetic fuels, and renewable energy demonstrates this well.

The difficulty arises from insufficient attention to the transition between the present and the desired future—the balance between forces that lock the energy economy in stasis and the entrepreneurial forces that could accelerate it toward a more beneficial condition.

In effect, the present competes against the future, and the pace and direction of any transition will be governed by the outcome. Viewing the transition to a hydrogen economy through the lens of a competitive transition can bring a set of "how" questions to the national policy debate—questions of how policy can rebalance the competitive forces so that change prevails in the marketplace.

A Model of the Competitive Transition

The competitive battle will be fought over a half century among three competing infrastructures:[1]

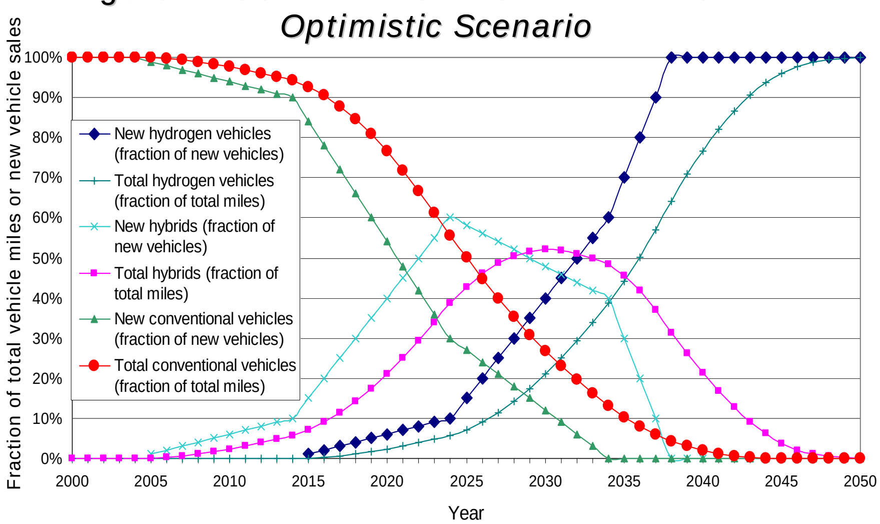
- The internal combustion engine (ICE), either in a spark-ignition or compression-ignition form, and its attendant motor fuels supply chain;
- The hybrid electric vehicle (HEV), now entering the market, which achieves superior efficiency by supplementing an internal combustion engine with an electric drive system and which uses the current supply chain for motor fuels; and,
- The hydrogen fuel cell vehicle (HFCV), which requires radically distinct technologies for the vehicle, for fuel-production, and for fuel distribution.

Figure 1 shows one scenario, based on the most optimistic assumptions, of how market share could shift among the contending infrastructures (NRC 2004). Several aspects of this scenario bear special mention. First, note the extended time required for meaningful change: these are long-lived assets built around large, sunk investments. They cannot be

[1] Another concept, the battery electric vehicle (BEV), offers an all-electric drivetrain with all on-board energy stored in batteries, which would be recharged from stationary sources when the vehicle is not in operation. I have not included this among the competitors because battery technology has not advanced rapidly enough for it to compete in highway markets. In contrast, BEV have proven quite successful in the personal transportation niche.

quickly changed under the best of circumstances. Second, the road to the hydrogen economy runs smoothest through the hybrid electric vehicle. The HEV offers immediate gains in fuel economy and advances technologies that will eventually prove useful for hydrogen fuel cell vehicles, especially battery and electric system management technologies. Although this scenario shows significant market penetration for the HEV, its success cannot be assured. The HEV might remain a niche product, despite its current popularity if consumers conclude that the value of the fuel savings does not compensate for the additional cost of the HEV. Or, its gains in efficiency might be directed toward vehicle size and acceleration rather than fuel economy. Either circumstance would make an early hydrogen transition even more desirable.

Figure 1: COMPETITION FOR MARKET SHARE
Optimistic Scenario



• *Complete replacement of ICE and HEV vehicles with fuel cell vehicles in 2050*

Source: NRC 2004

Any transition to a HFCV fleet, however, will require overcoming a key marketplace barrier that is unique to hydrogen—widely available supplies of fuel. And to this we now turn.

The Chicken and the Egg[2]

Most analyses suggest that large-scale production plants in a mature hydrogen economy can manufacture fuel at a cost that competes well with gasoline at current prices (NRC 2004). However, investors will not build these plants and their supporting distribution infrastructure in the absence of large-scale demand. And, the demand for hydrogen will not be forthcoming unless potential purchasers of hydrogen vehicles can be assured widely available sources of fuel. Variants of this "chicken and egg" problem have limited the market penetration of other fuels, such as methanol and ethanol blends (M85 and E85) and compressed natural gas. This issue—the simultaneous development of the supply side and demand sides of the market—raises one of the highest barriers to a hydrogen transition.

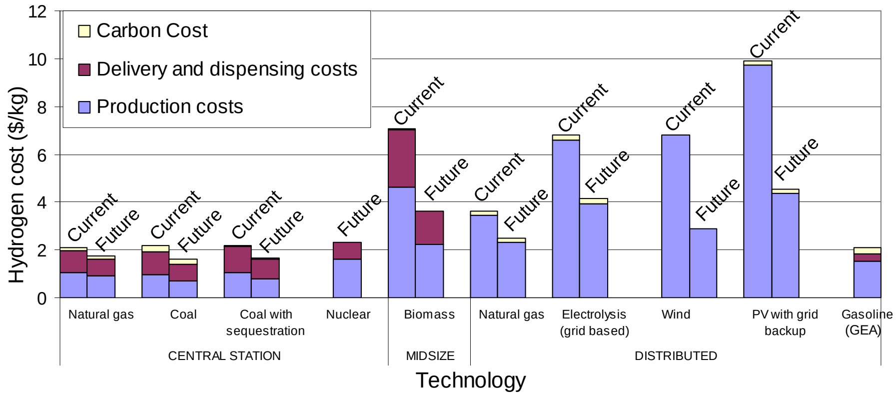
Distributed Hydrogen Production for the Transition

To resolve this problem, a committee of the National Academy of Sciences (NRC 2004) recommended an emphasis on distributed production of hydrogen. In this model, the hydrogen fuel would be manufactured at dispensing stations conveniently located for consumers. Once the demand for hydrogen fuel grew sufficiently, then larger manufacturing plants and logistic systems could be built to achieve scale economies. However, distributed production of hydrogen offers two salient challenges.

The first challenge is cost. Figure 2, below, shows the delivered cost of molecular hydrogen for a variety of production technologies. The "distributed" technologies,

[2] Alternatively framed: "Which comes first, the vehicle or the fuel?"

Figure 2: A SUPPLY CHAIN INFRASTRUCTURE
Delivered H_2 Costs of Alternative Technologies



• *GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency*

Source: NRC 2004

to the right in Figure 2, offer hydrogen at a cost between 2 and 5 times the cost of the large-scale, “central station” technologies, on the left in Figure 2. Technological advances can mitigate, but not remove entirely, this cost disadvantage.

The second challenge concerns the environment. Carbon capture and sequestration do not appear practical in distributed production. During the opening stage of a hydrogen transition, we might simply have to accept some carbon releases in order to achieve the later benefits.

<u>Research to Accelerate a Transition by Distributed Hydrogen Production</u>

A study panel conveniened by the National Academy of Sciences (NAS) recently recommended several research thrusts that could accelerate distributed production for a transition to hydrogen (NRC 2004). These include:

- Development of hydrogen fueling "appliance" that can be manufactured economically and used in service stations reliably and safely by relatively unskilled persons—station attendants and consumers.
- Development of an integrated, standard fueling facility that includes the above appliance as well as generation and storage equipment capable of meeting the sharply varying demands of a 24-hour business cycle.
- Advanced technologies for hydrogen production from electrolysis, essentially a fuel cell operated in reverse, to include enabling operation from intermittent energy sources, such as wind.
- Research on breakthrough technologies for small-scale reformers to produce hydrogen from fossil feedstocks.

The Department of Energy has adopted the NAS recommendations and modified its programs accordingly. It remains too early to judge progress, but in any case these technologies should receive continued emphasis as the desired transition to hydrogen nears. However, progress in research is notoriously difficult to forecast accurately. This suggests consideration be given to interim strategies that would work on the demand side of the marketplace, either to subsidize the cost of distributed hydrogen production while demand builds or to raise the cost of the competition, gasoline and diesel fuels. Such actions would relieve the research program of the entire burden for enabling the transition.

FUNDAMENTAL RESEARCH TO SUSTAIN A HYDROGEN ECONOMY

At the same time that the marketplace transition advances, several high-payoff (but also high-risk) research campaigns should be waged. These include:

- Storing hydrogen on-board vehicles at near-atmospheric pressure;
- Sequestering the carbon-dioxide effluent from manufacturing hydrogen from coal;
- Sharply reducing the cost of hydrogen produced from non-coal resources, especially nuclear, photobiological, photoelectrochemical, and thin-film solar processes;
- Improving the performance and cost of fuel cells; and,
- Storing electricity on-board vehicles in batteries that provide both high energy performance and high power performance at reasonable cost.

On-Vehicle Hydrogen Storage

The most important long-term research challenge is to provide a more effective means of storing hydrogen on vehicles than the compressed gas or cryogenic liquid now in use. In my judgment, failure to achieve this comes closer to a complete "show-stopper" than any other possibility. I believe this true for two reasons: hydrogen leakage as the vehicle fleet ages, and cost.

With regard to leakage, high pressure systems currently store molecular hydrogen on demonstration vehicles safely and effectively. But these are new and specially-built, and trained professionals operate and maintain. What can we expect of production run vehicles that receive the casual maintenance afforded most cars? A glance at the oilstained pavement of any parking lot offers evidence of the leakage of heavy fluids stored in the current ICE fleet at atmospheric pressure. As high pressure systems containing the lightest element in the universe age, we might find even greater difficulties with containment. With regard to cost, the energy losses from liquefaction and even compression severely penalize the use of hydrogen fuel, especially when manufactured at distributed stations.

The NAS Committee, cited earlier (NRC 2004), strongly supported an increased emphasis on game-changing approaches to on-vehicle hydrogen storage. One alternative could come from novel approaches to generating the hydrogen on board the vehicle.[3] Chemical hydrides, for example, might offer some promise here, such as the sodium borohydride system demonstrated by Daimler-Chrysler.

Carbon Sequestration

Domestic coal resources within the United States hold the potential to relieve the security burdens arising from oil dependence—but only if the environmental consequences of their use can be overcome. Further, as shown in Figure 2, coal offers the lowest cost pathway to a hydrogen-based energy economy, once the transient conditions have passed. Thus, the conditions under which this resource can be used should be established as soon as possible. The prevailing assumption holds that the carbon effluent from hydrogen manufacturing can be stored as a gas (carbon dioxide, or CO_2) in deep underground formations. Yet how long it must be contained and what leakage rates can be tolerated remain unresolved issues (Socolow 2005). Within the Department of Energy, the carbon

[3] I do not include on-board reforming of fossil feedstocks, like gasoline, among these. These syetems offer little gain beyond that achievable with the HEV, and most industrial proponents appear to have abandoned the idea.

sequestration program is managed separately from hydrogen and vehicles programs. The NAS committee recommended closer coordination between the two as well as an ongoing emphasis on carbon capture and sequestration (NRC 2004).

Producing Hydrogen Without Coal

Manufacturing hydrogen from non-fossil resources stands as an important hedge against future constraints on production from coal, or even from natural gas. And under any circumstance, the hydrogen economy will be more robust if served by production from a variety of domestic sources.

The non-fossil resource most immediately available is nuclear. Hydrogen could be produced with no CO2 emissions by using nuclear heat and electricity in the high-temperature electrolysis of steam. Here the technology issues include the durability of the electrode and electrolyte materials, the effects of high pressure, and the scale-up of the electrolysis cell. Alternatively, a variety of thermochemical reactions could produce hydrogen with great efficiency. Here the needed research concerns higher operating temperatures (700^{o}C to 1000^{o}C) for the nuclear heat as well as research into the chemical cycles themselves. In both cases, the safety issues that might arise from coupling the nuclear island with a hydrogen production plant bear examination (NRC 2004).

In addition, hydrogen production from renewable sources should be emphasized, especially that avoiding the inefficiencies of the conventional chain of conversions: (1) from primary energy into electricity; (2) from electricity to hydrogen; (3) from hydrogen to electricity on-board the vehicle; (4) from electricity to mobility, which is what the customer wanted in the first place. Novel approaches to using renewable energy, such as photobiological or photoelectrochemical, should be supported strongly (NRC 2004).

Improved Fuel Cells

The cost and performance of fuel cells must improve significantly for hydrogen to achieve its full potential. To be sure, molecular hydrogen can be burned in specially designed internal combustion engines. But doing so foregoes the efficiency gains obtainable from the fuel cell, and becomes a costly and (from an energy perspective) inefficient process. The NAS Committee thought the fuel cell essential for a hydrogen economy to be worth the effort required to put it in place. They recommended an emphasis on long-term, breakthrough research that would dramatically improve cost, durability, cycling capacity, and useful life.

Improved Batteries

The battery is as important to a hydrogen vehicle as to a hybrid because it serves as the central energy management device. For example, the energy regained from regenerative braking must be stored in a battery for later reuse. Though energy storage governs the overall operating characteristics of the battery, a high rate of energy release (power) can enable the electric motor to assist the HEV in acceleration and relieve the requirements for fuel cells to immediately match their power output with the needs of the vehicle. Thus, advanced battery research becomes a key enabler for the hydrogen economy and might also expand the scope of the BEV.

ENTREPRENEURSHIP FOR THE HYDROGEN ECONOMY

For the results of DoE research to gain traction in a competitive economy, entrepreneurs and corporate innovators must succeed in bringing hydrogen-related innovations to the marketplace. In many cases, independent entrepreneurs provide the pathbreaking innovations that lead to radical improvements in performance, while established companies provide continuous, accumulating improvement.[4] The federal government, in partnership with states and universities, can become an important enabler of both pathways to a hydrogen economy.

Federal Policies Promoting Entrepreneurship

From the federal perspective, several policies could be considered to build an entrepreneurial climate on the "supply" side of the market. These include:

- Special tax consideration for investors in new ventures offering products relevant to fuel savings. The intent would be to increase the amount of venture capital available to startup companies.
- Commercialization programs might enable more entrepreneurs to bring their nascent technologies up to investment grade. For example, an enhanced and focused *Small Business Innovation Research* (SBIR) program might increase the number of participating entrepreneurs participating in fuel-relevant markets. A portion of the *Advanced Technology Program* (ATP) could be focused in like manner.

[4] See the Appendix: The Process of Innovation and Implications for the Hydrogen Transition for a more complete discussion.

- Outreach from the National Laboratories to entrepreneurs might be improved. Some laboratories, the National Renewable Energy Laboratory (NREL) for example, offer small, but effective programs. But more systematic outreach, not to business in general, but to entrepreneurial business, would also increase the supply of market-ready innovations.

On the demand side, any policy that increases consumer incentives to purchase fuel efficient vehicles will provide an incentive for ongoing innovation—provided that the policy is perceived as permanent. Entrepreneurs and innovators respond primarily to opportunity; but that opportunity must be durable for the 10 year cycle required to establish a new, high-growth company.

States and Universities as Agents of Innovation/Entrepreneurship

Innovation/entrepreneurship is a contact sport, and that contact occurs most frequently and most intensely within the context of specific laboratories and specific relationships. I will use Clemson's International Center for Automotive Research (ICAR) to illustrate this principle. Most fundamentally, the ICAR is a partnership among the State of South Carolina, major auto makers,[5] and their Tier I, Tier II, and Tier III suppliers. The inclusion of these suppliers will be essential for the success of ICAR or any similar research venture. This is because innovation in the auto industry has evolved toward a global, networked process, much as it has in other industries like microelectronics. The "supply chain" is more accurately described as a network, and network innovation will replace the linear model.

[5] BMW was the founding OEM and most significant supporter of the ICAR.

For these reasons, the ICAR, when fully established, will serve as a channel for research and innovation to flow into the entire cluster of auto-related companies in the Southeast United States. We anticipate drawing together and integrating the best technology from a variety of sources:

- Research performed at Clemson University and at the ICAR itself;
- Research performed at the Savannah River National Laboratory and the University of South Carolina; and,
- Relevant science and technology anywhere in the world.

Beyond research, the ICAR will include two other components of a complete innovation package: education, and entrepreneur support. With regard to education, the Master of Science and PhD degrees offered through the ICAR will emphasize the integration of new technology into vehicle design, viewing the auto and its manufacturing plant as an integrated system. In addition, courses on entrepreneurship and innovation, offered through Clemson's Arthur M. Spiro Center for Entrepreneurial Leadership, will equip students with the skills to become effective agents of change within the specific context of the global motor vehicle industry.

With regard to entrepreneur support, the ICAR will host a state-sponsored innovation center to nurture startup companies that originate in the Southeast auto cluster and to draw others from around the world into that cluster. In addition, the ICAR innovation center will welcome teams from established companies seeking the commercial development of their technologies. The State of South Carolina has provided significant support through four recent legislative initiatives. The Research University

Infrastructure and the Research Centers of Economic Excellence Acts build the capabilities of the state's universities; and the Venture Capital Act and Innovation Centers Act provide support for entrepreneurs.

None of these elements can suffice by itself; but taken together they combine to offer a package of technology, education, and innovation that can serve the hydrogen transition extraordinarily well.

A CONCLUDING OBSERVATION

Revolutionary technological change of the kind contemplated here is rarely predictable and never containable. Every new technology from the computer to the airplane to the automobile carries with it a chain of social and economic consequences that reach far beyond the technology itself. Some of these consequences turn out to be benign; some pose challenges that must be overcome by future generations; but none have proven foreseeable.

For example, a hydrogen transition might bring prolonged prosperity or economic decline to the electric utility industry depending upon which path innovation takes. A pathway that leads through plug-hybrids to home appliances that manufacture hydrogen by electrolysis would reinforce the current utility business model. A pathway in which hydrogen fuel cell vehicles serve as generators for home electric energy would undermine that model. The same holds true for the coal industry. A future in which carbon sequestration succeeds will affect coal far differently from one in which it cannot be accomplished.

The only certainty is that the energy economy will be vastly different from that which we know today. It will have to be.

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U.S. National Research Council, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, The National Academies Press, 2004.

APPENDIX:[6]

THE PROCESS OF INNOVATION AND IMPLICATIONS FOR THE HYDROGEN TRANSITION

At the beginning, it might be helpful to review some general principles regarding technological innovation and how it advances performance throughout the economy. We should begin by understanding technology from the customer perspective—not as a "thing," but as a service.

[6] This Appendix draws heavily upon a previous statement prepared for the 9 February, 2005 hearing of the House Science Committee.

Technology Viewed as a Service

Fuels and vehicles have little value in themselves, but enormous utility as providers of mobility services. These valued services include performance vectors like:

- time saving: will the vehicle travel far enough that the driver does not waste time with frequent refueling?
- safety: how well does the vehicle protect its occupants, both by its ability to avoid accidents and by its ability to survive them?
- comfort: can the vehicle mitigate the stress and hassles of road travel for the driver and passengers?
- image: what does driving this particular vehicle say about its occupants?
- ancillary services: does the vehicle have enough generating capacity to meet the growing demand for onboard, electricity-based services?

At any time, consumers emphasize some of these performance dimensions while satisficing along others. Consider the consumer preferences revealed by an EPA analysis of automobile performance from 1981 to 2003. Over this period, average horsepower nearly doubled (from 102 to 197 horsepower), weight increased markedly (from 3201 to 3974 lbs), and the time required to accelerate from zero to 60 mph dropped by nearly 30 percent. An energy policy that added fuel security to the competitive performance dimensions for road transportation would do much to promote the hydrogen transition.

Technology-based Innovation: Accumulating

Technological innovations can be grouped into two general classes: those that advance performance by *accumulating* incremental improvements, and those that offer *discontinuous* leaps in performance. The term *accumulating* applies to technologies that advance performance along dimensions already recognized and accepted by customers. Each improvement might be incremental, but the cumulative effect compounds to yield markedly improved performance—consider the improvements in processor speed for computers, for example. Auto manufacturers are accustomed to competing along these dimensions, and the cumulative effect can lead to important advances—but only if the technology competition continues long enough for the gains to accumulate. Most of the fuel saving technologies discussed at this hearing are incremental in nature, and so nurturing this kind of innovation could become an important policy goal.

Technology-based Innovation: Discontinuous

In contrast, *discontinuous* technologies introduce performance dimensions quite distinct from what the mainstream customers have come to value, sometimes offering inferior performance along the accustomed dimensions. Because of their inferior mainstream performance, these technologies initially gain traction only in niche markets. With continued use and improvement, however, discontinuous technologies gain adequacy along the original dimensions and then enter the mainstream markets.

Consider the battery electric vehicle (BEV), for example. Many analysts have written off electric vehicles because of their inferior performance in mainstream auto markets—acceleration, range, and recharge time. Yet electric vehicle technologies are emerging in an important niche: the market for personal transportation. This includes golf carts, all-terrain vehicles, touring vehicles for resorts, transportation within gated communities, and so forth. In that market, the chief performance dimensions are convenient access, economy, and ease of use—and style. The current state of electric vehicle technology is adequate for the limited range and acceleration requirements of this niche. But, could electric vehicle technology advance to the point of entry into mainstream markets? Or, could it compete effectively in personal transportation markets in developing countries—say Thailand or China? That is, of course, unknowable. But, please recall that the personal computer was once considered a hobbyists toy, inherently without enough power to enter mainstream applications.

Discontinuous innovation tends to be the province of the *entrepreneur*, and the companies that such persons found become platforms for the innovations that radically change all markets. Yet entrepreneurs often have low visibility relative to the market incumbents in policy discussions, and their companies are far from household words.[i] This is because the entrepreneurs' story is about the future, not the present; about what could be and not about what is. For that reason, policies that encourage entrepreneurship in technologies relevant to the hydrogen transition should become part of the energy policy conversation.

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[i] Consider, for example, *Zap!*, a company founded 10 years ago in response to the zero-emissions vehicle market emerging in California. A description can be found at: http://www.zapworld.com/index.asp